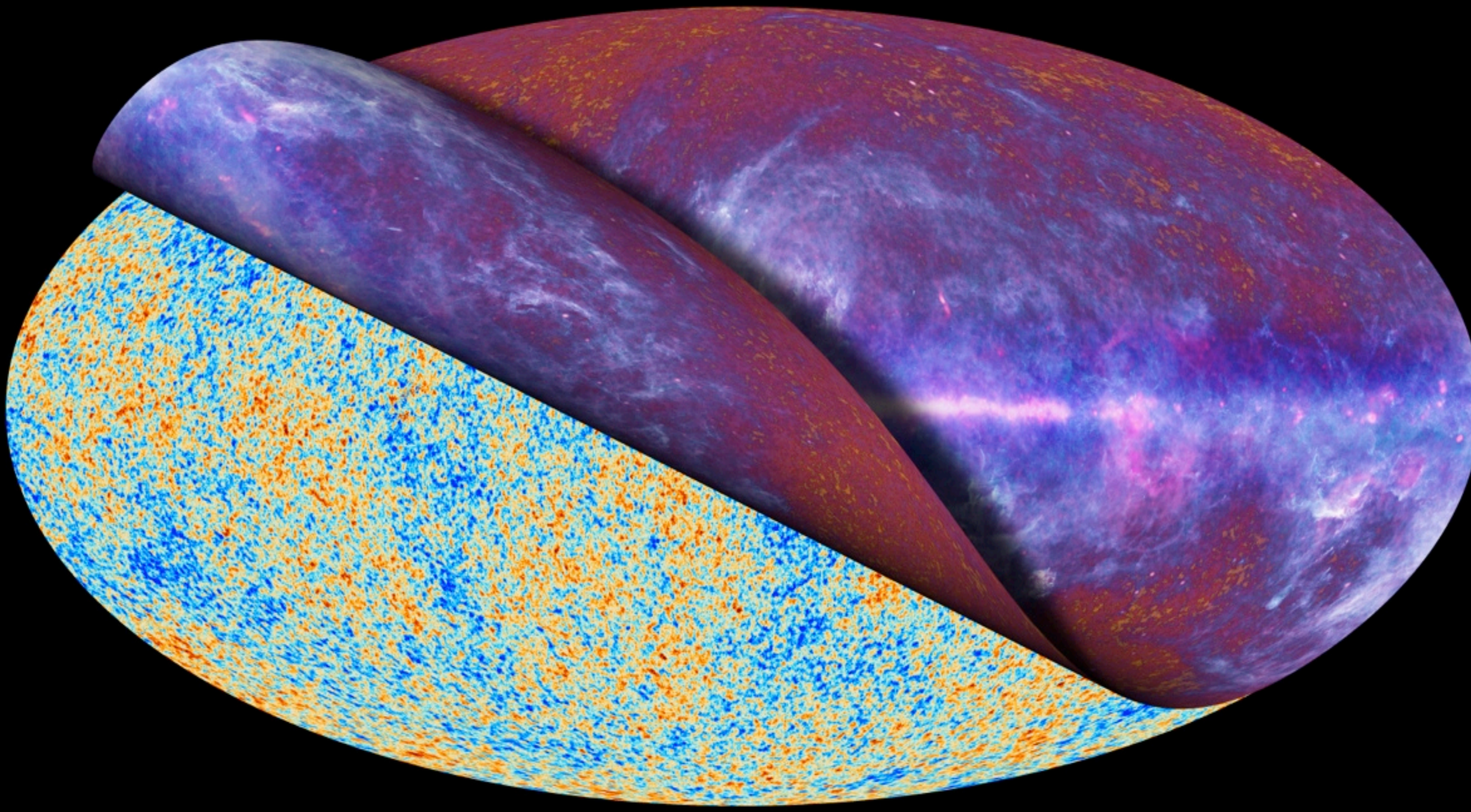
planck

esa



# Planck unveils the Cosmic Microwave Background

# PLANCK RESULTS AND NEUTRINO PHYSICS: CONSTRAINTS AND TENSIONS

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On behalf of the Planck Collaboration

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Presenting results from Planck papers XVI and XX

# The Cosmic Neutrino Background (CνB)

- The presence of a background of relic neutrinos is a basic prediction of the standard cosmological model
- Neutrinos decouple from the cosmological plasma at T ~ 1 MeV ( z ~ $10^{10}$ );
- Neutrinos keep the energy spectrum of a relativistic fermion in equilibrium:

$$f_\nu(p) = \frac{1}{e^{p/T} + 1}$$

- The present Universe is filled by a relic neutrino background with T = 1.9 K and n = 114 part/cm$^3$ (CnB)

- Neutrinos are nonrelativistic today…

$$\rho_\nu = m_\nu n_\nu = m_\nu g_\nu \int f(p) d^3 p \propto m_\nu g_\nu T_\nu^3$$

$$\Longrightarrow \quad \Omega_\nu = \sum_\nu \frac{\rho_\nu}{\rho_c} = \frac{\sum_\nu m_\nu}{93.14 h^2\ \mathrm{eV}}$$

- … but they were ultrarelativistic in the early Universe

$$\rho_\nu = g_\nu \int p\, f(p) d^3 p \propto g_\nu T_\nu^4$$

$$\rho_{\mathrm{rad}} = \rho_\nu + \rho_\gamma = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_\nu\right]\rho_\gamma$$

- The latter is recast as a ***definition*** the $N_{eff}$ parameter:

$$\rho_{\rm rad} \equiv \rho_\nu + \rho_\gamma = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right]\rho_\gamma$$

i.e.,

$$N_{\rm eff} \equiv \frac{\rho_{\rm rad} - \rho_\gamma}{\rho_\nu^{\rm (std)}}$$

indeed, also assuming a the standard thermal history, $N_{eff}$ =3.046 (Mangano et al., 2005)

In general, $N_{eff}$ parameterizes the presence of extra radiation components ("dark" radiation, not necessarily associated to neutrinos) in the early Universe.

But remind that – neutrinos not being really massless - an exact calculation of the perturbation evolution would require to specify *the full form of the distribution function.*

# Probing the neutrino mass with CMB data

The effect of neutrinos with a mass between $10^{-3}$ and 1 eV on the primary CMB spectrum comes from the fact that they contribute to the radiation density at the time of equality, and to the nonrelativistic matter density today.

This induces an integrated Sachs-Wolfe effect (both at early and late times) and/or a change in the angular diameter distance to the last scattering surface.

Before Planck, these were the dominant effects in constraining the neutrino mass from CMB data.

The situation circa January 2013

| | |
|---|---|
| $\sum m_\nu < 1.3\text{eV}$ | WMAP9 |
| $\sum m_\nu < 0.44\text{eV}$ | WMAP9+eCMB+BAO+HST |
| $\sum m_\nu < 0.70\text{eV}$ | WMAP7 + ACT |
| $\sum m_\nu < 0.39\text{eV}$ | WMAP7+ACT+BAO+HST |
| $\sum m_\nu < 1.60\text{eV}$ | WMAP7+SPT |
| $\sum m_\nu < 0.66\text{eV}$ | WMAP7+SPT+BAO+HST |

(Sievers et al 2013; Hinshaw et al 2013; Hou et al 2013)

(95% errors unless otherwise stated)

# Probing the neutrino mass with CMB data

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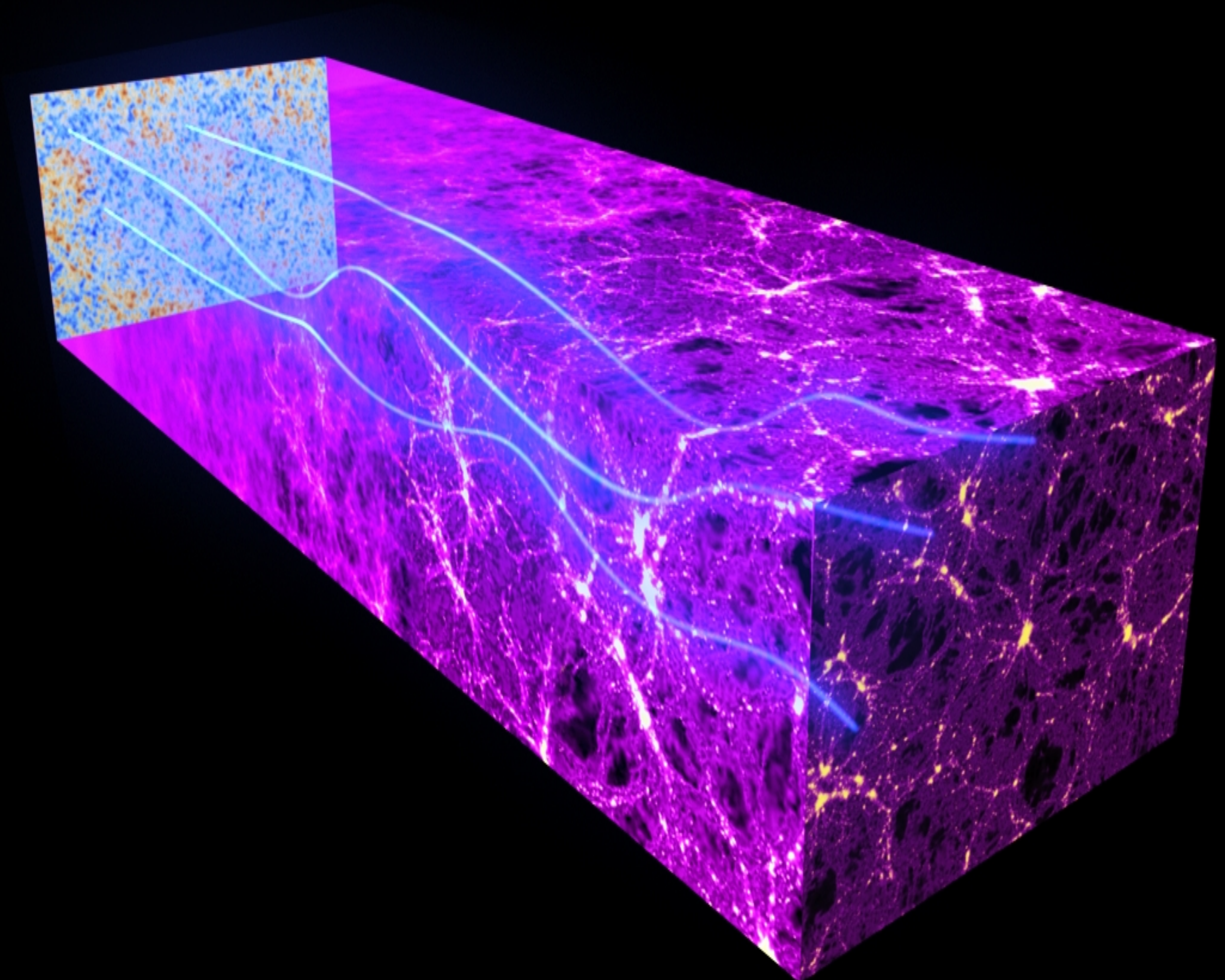
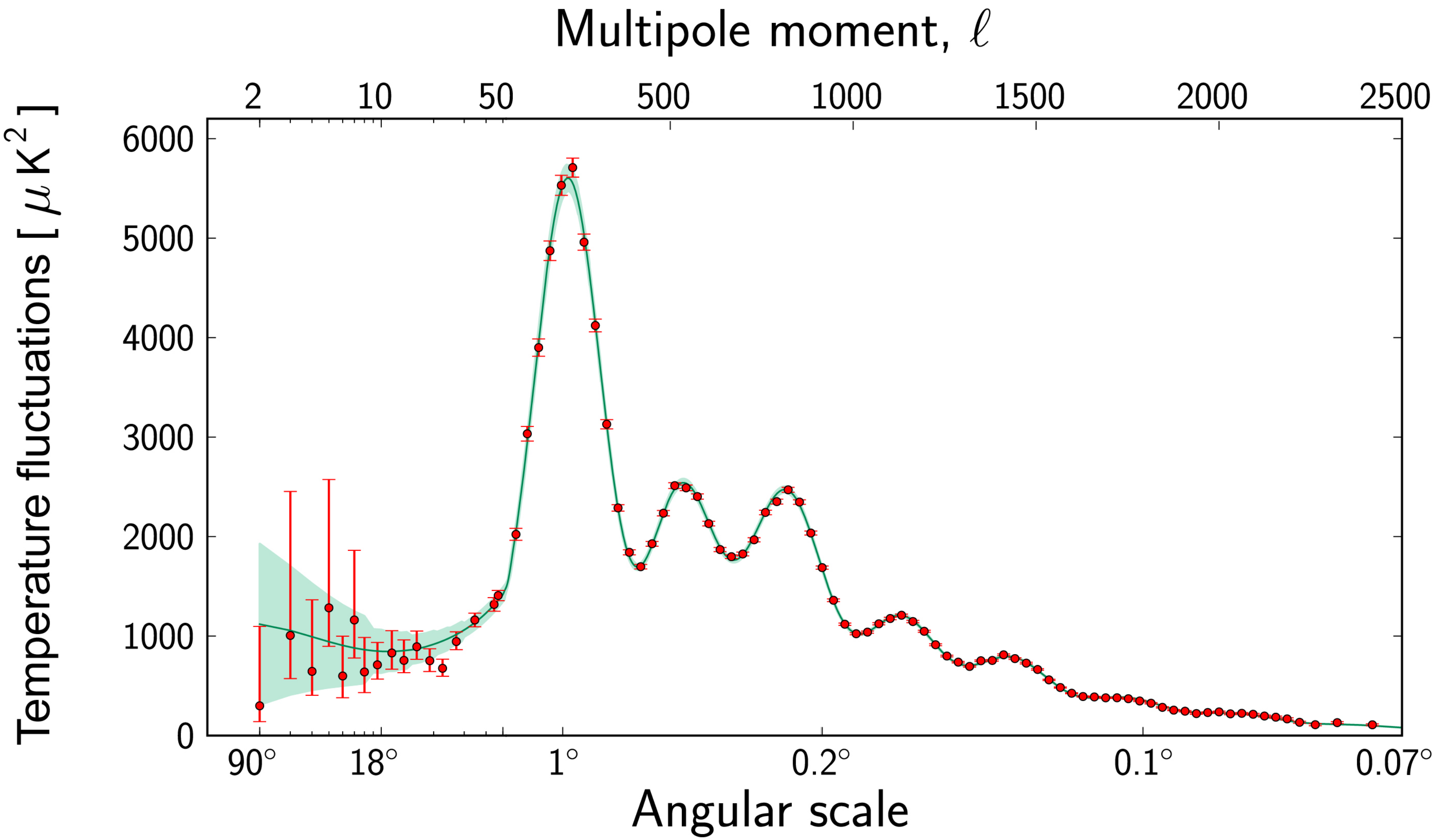
Before Planck, these were the dominant effects in constraining the neutrino mass from CMB data.

***Planck has moved us to a new regime where instead the dominant effect is gravitational lensing.***

Increasing the neutrino mass suppresses clustering on scales smaller than the size of the horizon at the time of the NR transition.



# Constraints on neutrino mass

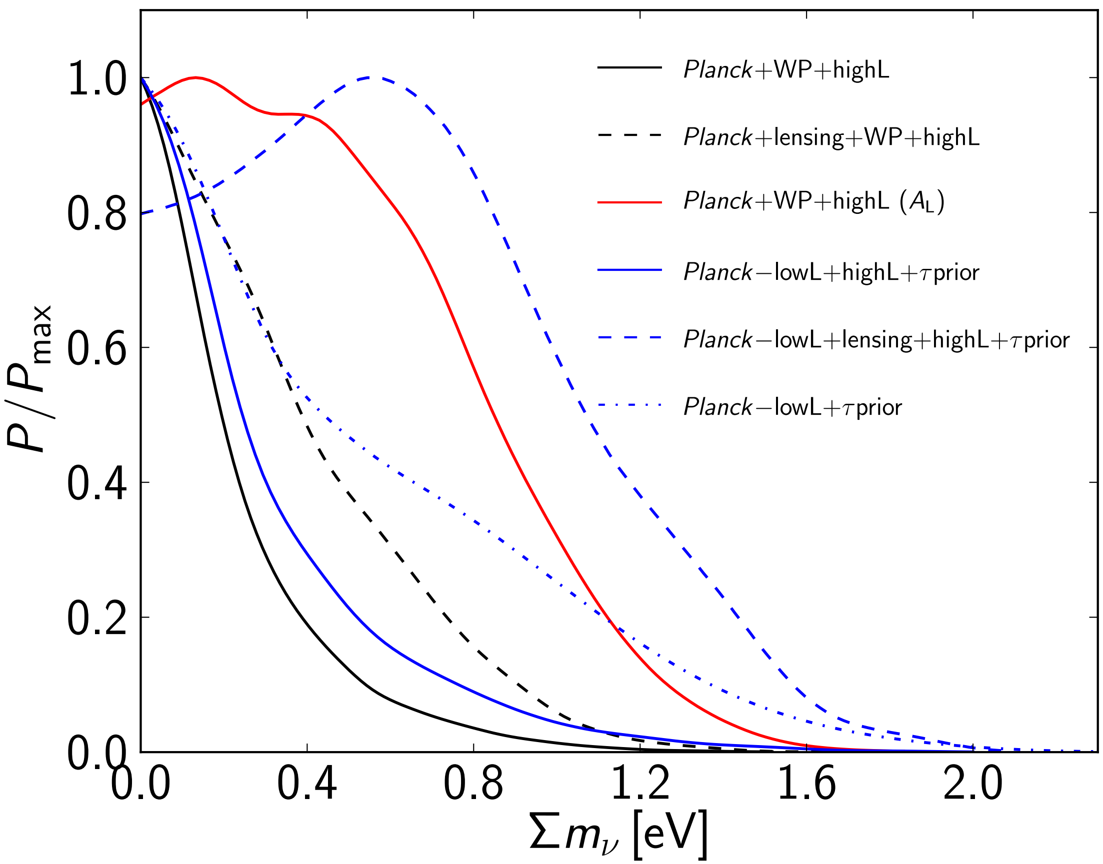


# Probing the neutrino mass with CMB data

We quote constraints on the parameters obtained using different combinations of the following datasets:

- the Planck temperature power spectrum. This includes the effect of lensing of the CMB by large scale structures (***Planck***);
- small-scale CMB experiments data. In particular we use the measurements of the TT power spectrum from ACT in the region 540 < l < 9440 and from SPT in the region 2000 < l <10000 (***highL***).
- the large angular scale EE polarization data from WMAP9 (***WP***);
- the information on the amplitude of the lensing spectrum from the Planck trispectrum (i.e., < TTTT> ) data (***lensing***)
- other astrophysical probes (BAO, SNIa, H0)

# Constraints on neutrino mass




$\Sigma m_\nu$ < 0.93 eV (Planck+WP)

$\Sigma m_\nu$ < 0.66 eV (Planck+WP+highL)

$\Sigma m_\nu$ < 0.25 eV (Planck+WP+BAO)

$\Sigma m_\nu$ < 0.23 eV (Planck+WP+highL +BAO)

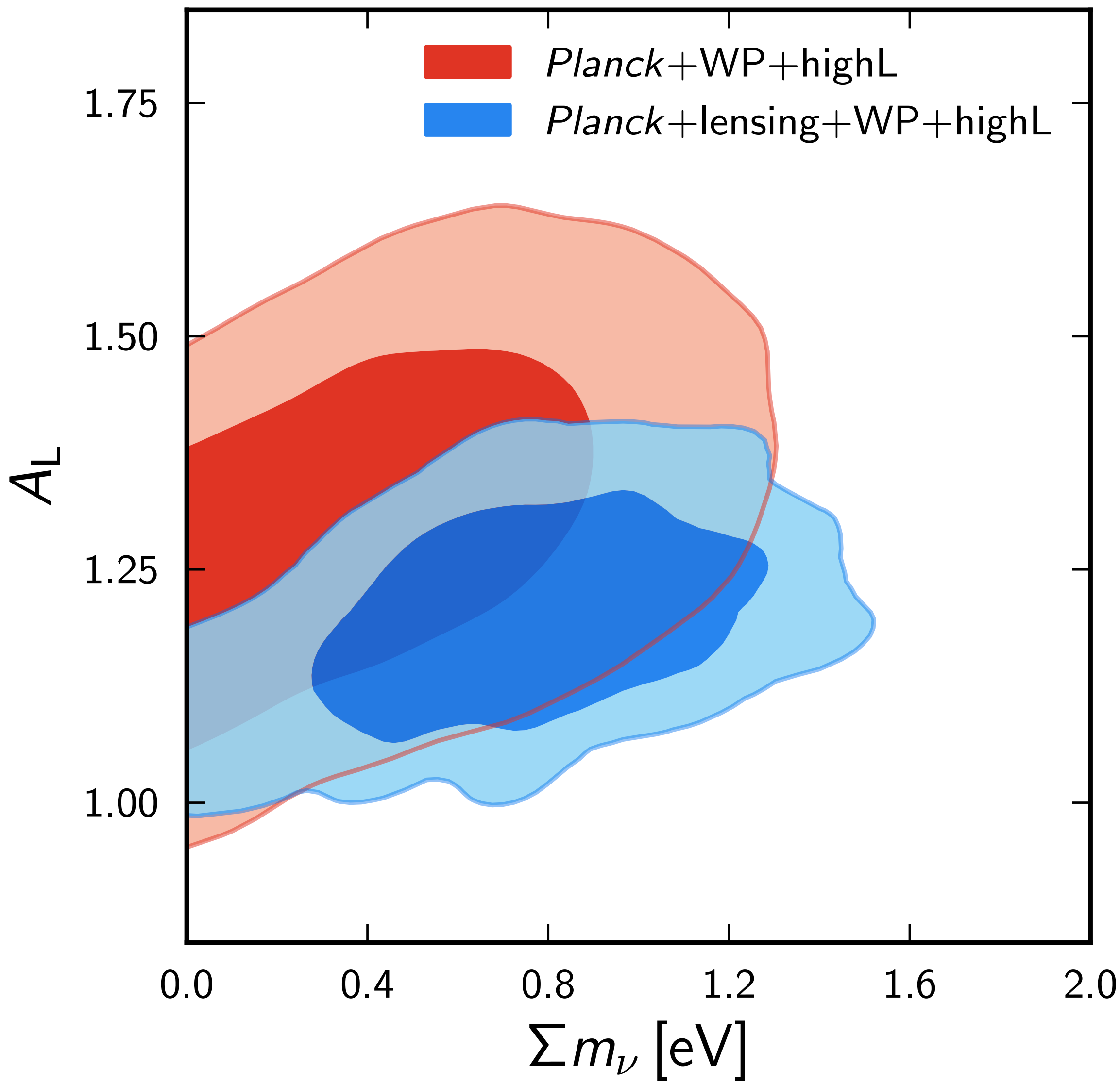
$\Sigma m_\nu$ < 1.08 eV [Planck+WP+highL ($A_L$)]

$\Sigma m_\nu$ < 0.85 eV (Planck+lensing +WP+highL)

(all limits are 95% CL)

- the posterior broadens when the lensing information is removed from the TT spectrum
- the constraint is also degraded when we add the information on the lensing spectrum itself (as estimated from the temperature trispectrum TTTT)
- this is because the 4-point function has a mild preference for larger masses wrt the 2-point function

# Constraints on neutrino mass



# Probing $N_{eff}$ with CMB data

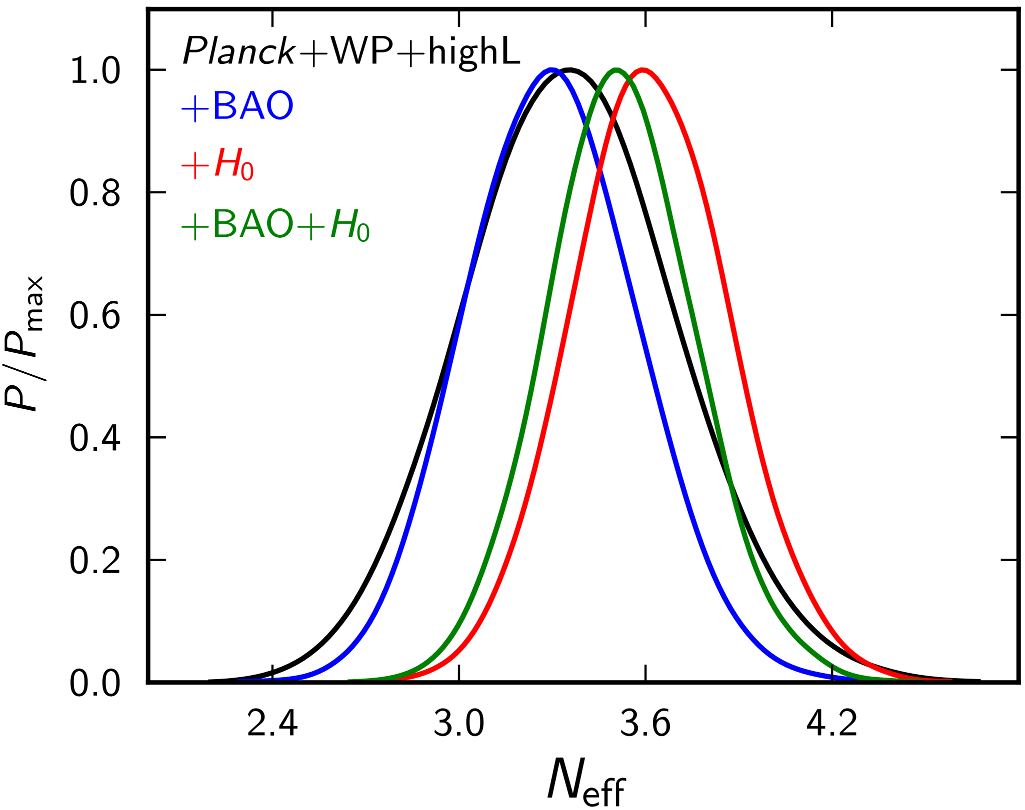
$N_{eff}$ parameterizes the density of radiation (other than photons) in the Universe, in units of the density of a single neutrino family in thermodynamic equilibrium at T=1.9 K. The standard value is $N_{eff}$ = 3.046

An excess in $N_{eff}$ could be caused by a neutrino/antineutrino asymmetry, sterile neutrinos, or other light relics in the Universe. The case $N_{eff} < 3.046$ is also possible (e.g. low reheating scenarios).

The main effect of increasing $N_{eff}$ while keeping both $\theta_*$ and $z_{eq}$ fixed is to increase the expansion rate before recombination and thus make the Universe younger at recombination. This increases the angular scale of the photon diffusion length and thus reduces the power in the damping tail.

$N_{eff}$ is correlated mainly with $H_0$, $Y_p$ and $n_s$.

# Probing $N_{eff}$ with CMB data




For Planck + other CMB datasets:

$$N_{\rm eff} = 3.51^{+0.80}_{-0.74} \quad \text{(Planck+WP)}$$

$$N_{\rm eff} = 3.36^{+0.68}_{-0.64} \quad \text{(Planck+WP+ highL)}$$

$$N_{\rm eff} = 3.39^{+0.77}_{-0.70} \quad \text{(Planck+WP+lensing)}$$

$$N_{\rm eff} = 3.28^{+0.67}_{-0.64} \quad \text{(Planck+WP+highL+ lensing)}$$

(all limits are 95% CL)

- $N_{eff}$ = 0 is excluded at ~ 10 sigma
- both $N_{eff}$ = 3 and $N_{eff}$ = 4 are always within $2\sigma$

The situation circa January 2013

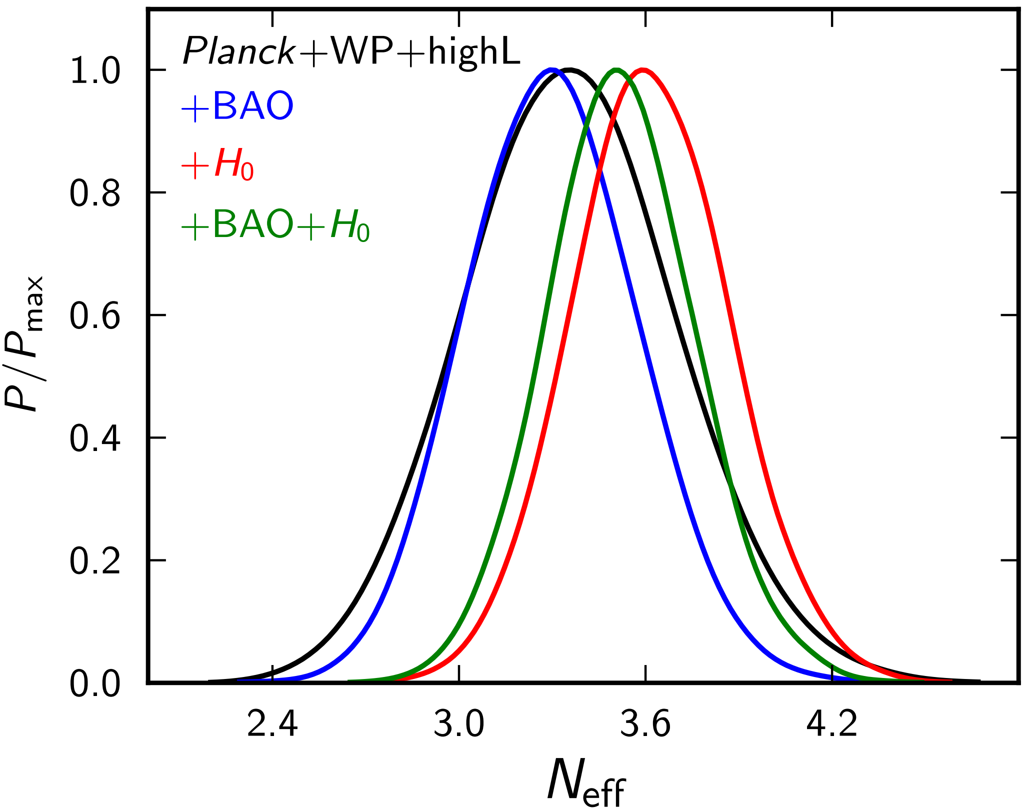
| | |
|---|---|
| $N_{\rm eff} > 1.7$ (95% CL) | WMAP9 |
| $N_{\rm eff} = 3.84 \pm 0.40$ | WMAP9+eCMB+BAO+HST |
| $N_{\rm eff} = 2.79 \pm 0.56$ | WMAP7 + ACT |
| $N_{\rm eff} = 3.50 \pm 0.42$ | WMAP7+ACT+BAO+HST |
| $N_{\rm eff} = 3.62 \pm 0.48$ | WMAP7+SPT |
| $N_{\rm eff} = 3.71 \pm 0.35$ | WMAP7+SPT+BAO+HST |

(Sievers et al 2013; Hinshaw et al 2013; Hou et al 2013)

(68% error unless otherwise stated)

# Probing $N_{eff}$ with CMB data

For Planck + astrophysical datasets:




$$N_{eff} = 3.40^{+0.59}_{-0.57}$$ (Planck+WP+BAO)

$$N_{eff} = 3.68^{+0.77}_{-0.78}$$ (Planck+WP+SNLS)

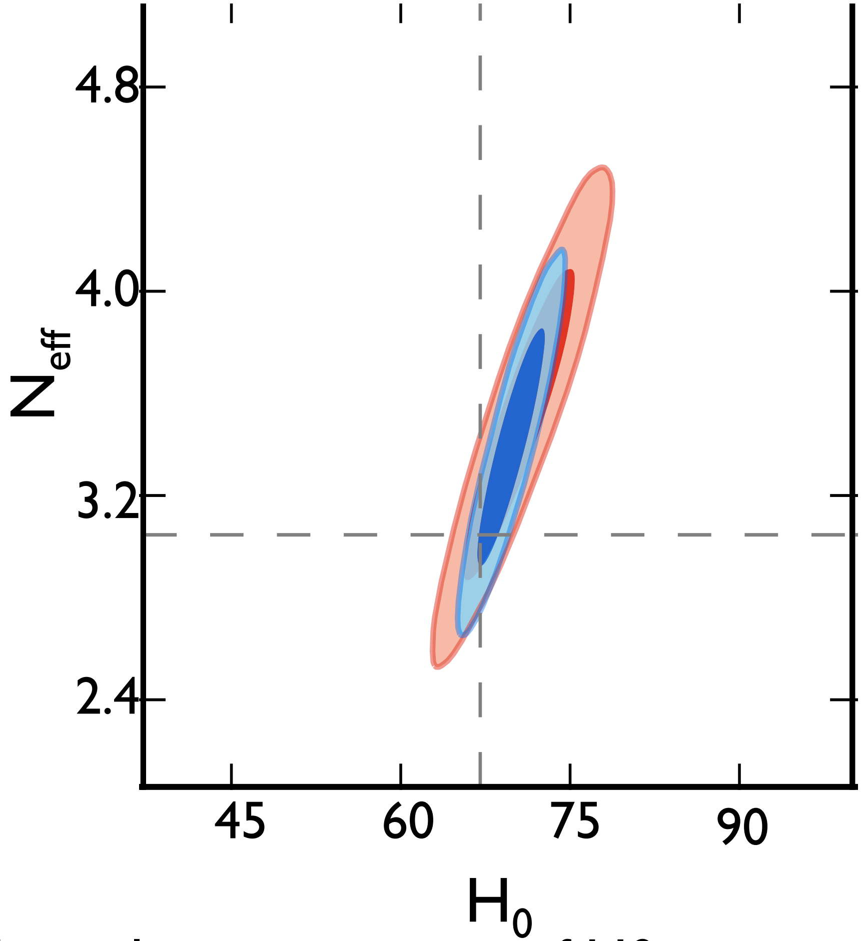
$$N_{eff} = 3.56^{+0.77}_{-0.73}$$ (Planck+WP +UNION2)

$$N_{eff} = 3.73^{+0.54}_{-0.51}$$ (Planck+WP+H0)

(all limits are 95% CL)

- The result with H0 is clearly driven by the tension between Planck and HST on the value of the Hubble constant

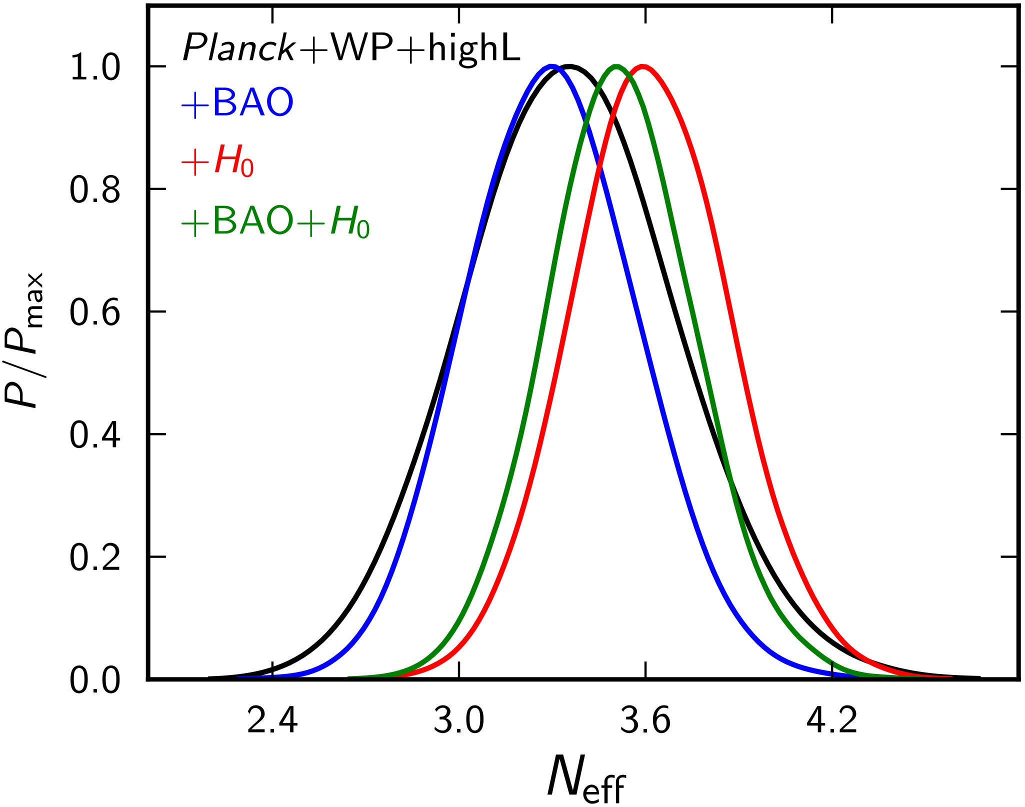
# Probing $N_{eff}$ with CMB data




- however, astrophysical measurements of H0 are moving towards h = 0.71….
- that incidentally is the same as the Planck mean posterior value for the LCDM+$N_{eff}$ model ($H_0$ = 70.7 + 3.0 – 3.2 km/sec/Mpc).

# Probing $N_{eff}$ with CMB data

For CMB + astrophysical datasets:




$N_{eff} = 3.30^{+0.54}_{-0.51}$ (CMB+BAO)

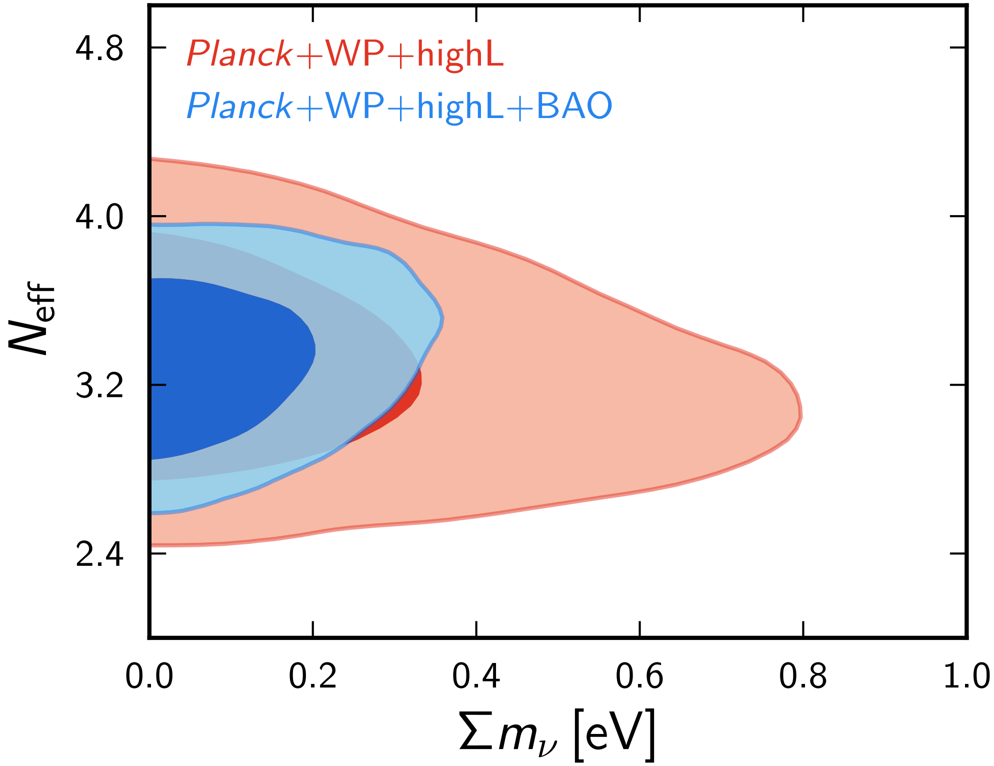
$N_{eff} = 3.51^{+0.67}_{-0.63}$ (CMB+SNLS)

$N_{eff} = 3.40^{+0.67}_{-0.63}$ (CMB + WP + UNION2)

$N_{eff} = 3.62^{+0.50}_{-0.48}$ (CMB+WP+H0)

(all limits are 95% CL)

# Joint constraints on $N_{eff}$ and $\Sigma m_\nu$



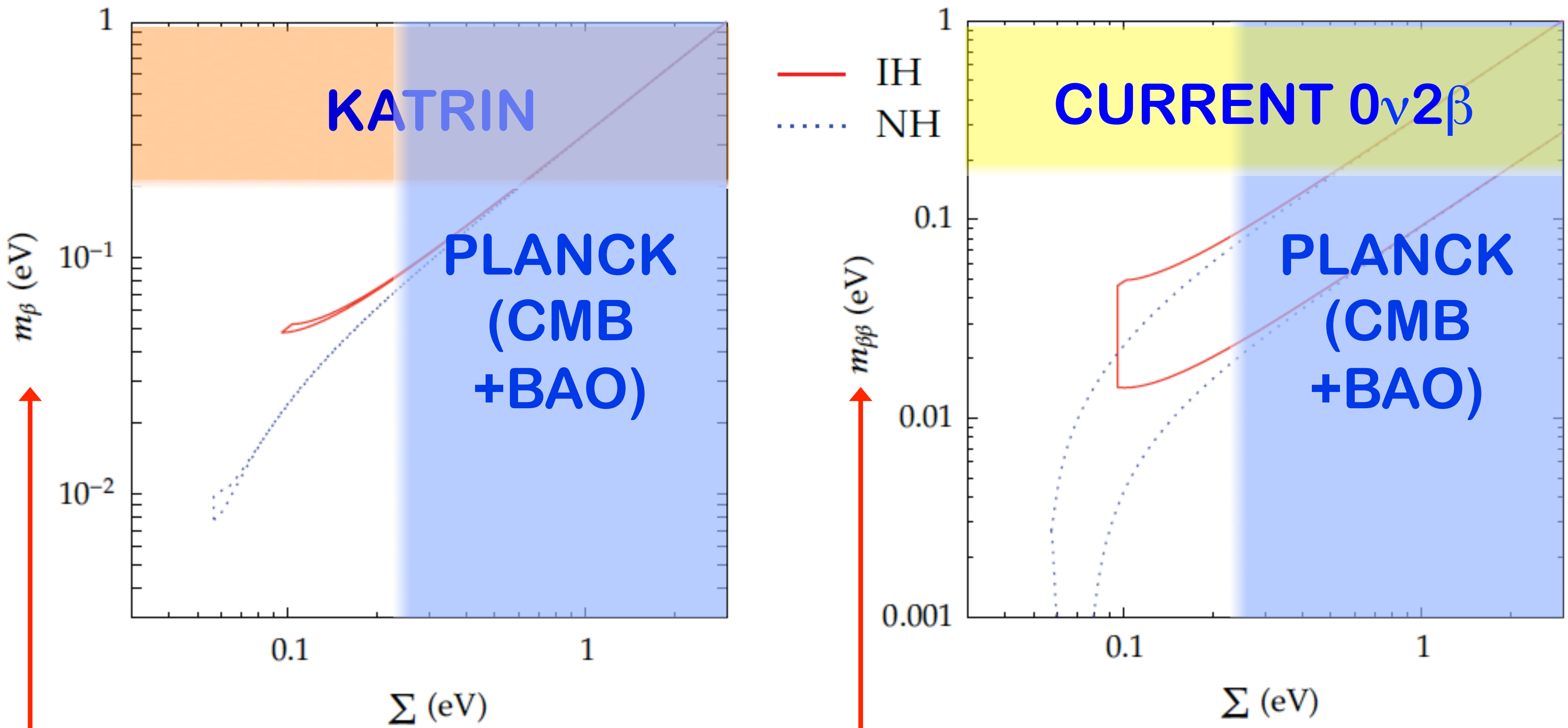

$N_{eff} = 3.29 + 0.67 - 0.64$
$\Sigma m_\nu < 0.60$ eV

Planck+WP +highL

$N_{eff} = 3.32 + 0.54 – 0\ .52$
$\Sigma m_\nu < 0.28$ eV

Planck+WP +highL + BAO

# Tritium β decay, 0ν2β and Cosmology




$$[c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2]^{1/2}$$

$$|c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3}|$$

The scientific results that we present today are the product of the Planck Collaboration, including individuals from more than 50 scientific institutes in Europe, the USA and Canada

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